

OXYGEN UPTAKE KINETICS IN SEVERE INTENSITY EXERCISE

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The purpose of this study was to describe mathematically the oxygen uptake kinetics during cycle ergometry, and to examine the effect of intensity on the kinetic responses within the severe domain. Sixteen volunteers performed a series of exercise tests at a range of intensities selected to elicit fatigue in ~3 to 10 min. A simple mono-exponential model effectively described the response across all intensities. There was a positive correlation between the response time and the time to fatigue, demonstrating that the maximal oxygen uptake was achieved faster at higher intensities within the severe domain. Models incorporating two components effectively described the responses only in tests lasting 8 min or more. It was concluded that there is a second, slow component in the oxygen uptake response only at the lower intensities within the severe domain.

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## CHAPTER 1

### INTRODUCTION

Whipp and Mahler (1980) and Gaesser and Poole (1996) have defined three domains of exercise intensity based upon their distinct metabolic profiles. During exercise in the moderate intensity domain, which encompasses work rates (WR's) at or below the lactate threshold (LAT), oxygen uptake ( $\text{VO}_2$ ) demonstrates rapid kinetics, rising with a gain of  $\sim 10 \text{ ml} \cdot \text{min}^{-1} \cdot \text{W}^{-1}$  to achieve a steady state within 3 min in healthy young individuals (Whipp, 1994). During exercise in the heavy domain, which includes WR's above the LAT, evidence shows that a slow component of the  $\text{VO}_2$  kinetics is superimposed upon the rapid response, resulting in a delayed steady state. The slow component represents an excess  $\text{VO}_2$  that elevates the gain, but the  $\text{VO}_2$  does not reach a maximal value ( $\text{VO}_{2\text{max}}$ ). During fatiguing exercise at yet higher WR's, within the severe domain, the  $\text{VO}_2$  increases to  $\text{VO}_{2\text{max}}$  (Gaesser & Poole; Whipp).

Although exercise intensity domains are clearly defined, the kinetic responses within each are not as well differentiated. Specifically, the pulmonary gas exchange responses within the severe domain have been less well characterized than those within the moderate and heavy domains.

#### Purpose

The primary purpose of this study was to describe mathematically the  $\text{VO}_2$  kinetics during cycle ergometry within the severe intensity domain. A secondary purpose was to examine the effect of intensity on the kinetic responses within the severe domain.

## Hypotheses

The first working hypothesis was that the  $\text{VO}_2$  response profile for exercise at all intensities within the severe domain would be well described by one-component models. The second hypothesis was that a slow component would be present only at lower intensities within the severe domain. Specifically, it was hypothesized that models that include two components would adequately describe responses only in longer tests (i.e., lower intensities) within this domain. The third hypothesis was that response kinetics would be faster at higher intensities. Specifically, it was hypothesized that there would be a significant negative relationship between WR and the rate of response ( $\tau$ ) and that there would be a significant positive correlation between time to fatigue ( $T_{\text{fat}}$ ) and the  $\tau$  for each individual.

## Delimitations

The study was delimited in the following ways:

1. The participants were 13 healthy students from the University of North Texas exercise physiology courses and 3 healthy students from Southwestern University.
2. Participants performed a total of 8-12 cycle ergometer tests (1 incremental test and 7-11 constant power tests).
3. The first two constant power tests were considered practice trials and were not used in statistical analyses.
4. Each participant was tested at the same time each day.

## Limitations

The study was limited in the following ways:

1. Only college-aged subjects were tested; therefore, the results may not be generalizable to a more diverse population.
2. Participants may not have given a maximal effort during all testing trials.
3. Participants may have had localized muscular fatigue due to previous test trials.
4. Participants may not have been tested across the full range of the severe intensity domain.
5. Because participants performed only one test at each exercise intensity, interbreath fluctuations of gas exchange may have occurred making it difficult to fit the data accurately to a mathematical model.



## CHAPTER 2

### LITERATURE REVIEW

The purpose of this study was to describe mathematically oxygen uptake ( $\text{VO}_2$ ) kinetics within the severe intensity domain, and to characterize the effect of intensity on the response. This chapter reviews the literature that describes the three phases that can be present in the  $\text{VO}_2$  response to exercise, the nature of the  $\text{VO}_2$  response within each exercise intensity domain, and the effect of intensity on kinetics with the severe domain.

#### Three Phases in the Pulmonary $\text{VO}_2$ Response to Exercise

Three phases of the response of pulmonary  $\text{O}_2$  uptake during the transition from rest or unloaded cycling to steady-state moderate have been described (Barstow, 1994; Whipp, 1994; Whipp, Ward, Lamarra, Davis, & Wasserman, 1982). The early, usually rapid response (Phase I), is seen in the first 15-25 s of exercise, and is thought to be due primarily to the initial surge of blood coming to the lungs from the extremities. The slower, exponential increase (Phase II) reflects decreased venous  $\text{O}_2$  content along with a continued increase in cardiac output. The  $\text{VO}_2$  rises in an exponential fashion toward a steady state for moderate exercise (below the lactate threshold (LAT)). The Phase II kinetics are thought to reflect the kinetics of muscle  $\text{O}_2$  utilization. Phase III is observed only in exercise at intensities above the LAT and only after about 2 min of exercise. If present, Phase III represents the effect of a slow component, leading to attainment of a

higher steady state value for  $\text{VO}_2$  (in heavy exercise) or to a maximal value ( $\text{VO}_{2\text{max}}$ ) (in severe exercise).

Thus, there may be as many as three distinct phases whose correct mathematical description would require at least nine parameters (i.e., the delay, gain, and rate of response for each phase) in the  $\text{VO}_2$  response. However, authors often describe the profile using fewer phases and/or parameters, and many curve-fitting techniques have been examined.

For example, several studies (Hill, Poole, & Smith, 1999; Hill, Williams, & Burt, 1997; Hughson & Morrissey, 1982; Whipp, 1994; Whipp et al., 1982) have described kinetic responses assuming a mono-exponential increase that begins immediately at the onset of exercise,

$$\text{VO}_2(T) = \text{VO}_{2\text{baseline}} + (\text{VO}_{2\text{fastgain}} \cdot (1 - e^{(-T/\tau)})).$$

Another mono-exponential model incorporates a time delay ( $T_D$ ) parameter, and has also been used to describe the  $\text{VO}_2$  responses to exercise (Hughson & Morrissey; Whipp et al.),

$$\text{VO}_2(T) = \text{VO}_{2\text{baseline}} + (\text{VO}_{2\text{fastgain}} \cdot (1 - e^{(-(T-T_D)/\tau)})).$$

This model permits derivation of a value for the time constant ( $\tau$ ) without forcing the increase in  $\text{VO}_2$  to occur in concert with the onset of exercise. Thus, the overall rate of change, or the mean response time (MRT), of the response can then be obtained from the sum of  $\tau$  and  $T_D$ . Using the latter model, if the  $T_D = 0$ , the model will converge down to the initial mono-exponential model with no  $T_D$ .

$\text{VO}_{2\text{max}}$  is essentially attained when the value of  $(1 - e^{(-T/\tau)})$  from the model without a  $T_D$  is 0.99. This occurs when  $T = (4.6 \cdot \tau)$ . Therefore, time to  $\text{VO}_{2\text{max}}$  ( $T_{\text{VO}_{2\text{max}}}$ ) could be defined as  $4.6 \cdot \tau$ .

For exercise above the LAT, double-exponential models have been examined (Barstow & Molé, 1991). The Phase II  $\text{VO}_2$  response has been fit to a double-exponential model where both terms begin after a common  $T_D$  close to the start of Phase II. However, other models have suggested that the onset of the second term may be delayed relative to the start of exercise and to the start of the first exponential term. This would allow the second exponential term to start after a second independent  $T_D$ . However, if the processes actually did begin at the same time, then the estimate for  $T_D$  would converge to that for the first one, and the equation would reduce to the first double-exponential model.

#### $\text{VO}_2$ Response Profile in Moderate Intensity Exercise

The moderate intensity domain includes all work rates (WR's) which can be accomplished without the induction of a sustained lactic acidosis, i.e., below the LAT. Within this domain, there is no lactate buildup, and  $\text{VO}_2$  increases and then levels off at a submaximal value. The exercise oxygen uptake increases as a linear function of WR to the maximal level. The  $\text{VO}_2$  increases rapidly in a mono-exponential fashion with a  $\tau$  of  $\sim 45$  s, and then reaches a steady state within about 3 min (Gaesser & Poole, 1996).

Whipp et al. (1982) examined characteristics of the  $\text{VO}_2$  response during moderate intensity exercise. Six participants performed eight repetitions of 100 W constant-load cycling preceded either by rest or unloaded pedaling. The data were fit to a simple exponential model with no  $T_D$ , an exponential response incorporating a  $T_D$ , or an

exponential response constrained to start only at the “inflection point” of the response (after Phase I). The characteristics of the corresponding dynamic responses differed for the two base-line conditions; i.e., rest and unloaded pedaling. From rest, an initial abrupt Phase I response accounted for 39% of the steady state  $\text{VO}_2$  increment, and the following exponential response began 19 s after the onset of exercise. For exercise from a baseline of unloaded pedaling, an early phase also became apparent, which after a clear inflection point, was followed by a further exponential rise. Although the response of this early phase rose more smoothly than that of exercise from rest, and accounted for only 19% of the steady-state  $\text{VO}_2$  increment, the duration of the first phase was similar (i.e., 19 s). According to Whipp et al., moderate exercise is not well described by a single-exponential function that begins at the work transition. However, if Phase I is excluded from analyses, gas exchange may be well described as a mono-exponential process, both from rest and from unloaded pedaling. It must also be noted that different strategies for considering the  $T_D$  component could markedly influence the value for the best-fit  $\tau$  to the  $\text{VO}_2$  response. Whipp (1994) stated that the most appropriate method for estimating the Phase II  $\tau$  should ignore the  $\text{VO}_2$  change during Phase I when fitting the curve.

#### $\text{VO}_2$ Response Profile in Heavy Intensity Exercise

The heavy intensity domain includes all WR's above the LAT but below critical power (CP; the asymptote of the relationship between WR and time to fatigue ( $T_{\text{fat}}$ )). During heavy exercise, blood lactate accumulates in the blood. The upper boundary to heavy exercise is the highest WR at which blood lactate can be stabilized, although at an elevated level (Poole, Ward, Gardner, & Whipp, 1988).

The kinetics of exercise at higher intensities are more complicated than the mono-exponential response seen in moderate exercise. At intensities such as this (above the LAT), another component is also necessary to describe the constant power  $\text{VO}_2$  response (Gaesser & Poole, 1996; Whipp, 1994; Barstow & Molé, 1991; Barstow, 1994). A slow phase of  $\text{VO}_2$  kinetics, referred to as the  $\text{VO}_2$  slow component, is superimposed upon the rapid response, resulting in a delayed steady state. The slow component results in a greater  $\text{VO}_2$  than would be expected from the  $\text{VO}_2$ -WR relationship in moderate exercise. Thus, 80-110 s after the onset of exercise, the slow component of  $\text{VO}_2$  becomes superimposed upon the rapid initial increase that is associated with exercise onset. For exercise in this domain, the slow component appears to develop most rapidly early in the exercise bout (i.e., min 3-10). As a result, the oxygen cost per unit of work increases and the efficiency of work decreases as a function of time (Gaesser & Poole).

Barstow (1994) examined the kinetics of  $\text{VO}_2$  during several transitions from unloaded cycling to each of several WR's in the heavy exercise domain. After the first 15-20 s, representing the Phase I response, were eliminated, the responses were then described using a double-exponential equation. The overall time constant increased with exercise intensity; however, the fast time constant was invariant across the exercise intensities.

Hughson and Morrissey (1982) examined the kinetics of the  $\text{VO}_2$  response in the transition from rest, or from prior exercise, to step increases in WR. Participants exercised within both the moderate and heavy intensity domains, but most exercise was performed below the LAT. Six participants each underwent three step increase tests from

rest to 80% of the WR at LAT, rest to 40% of the WR at LAT, 40 to 80% of the WR at LAT, rest to 40% of the WR at LAT, and 40 to 120% of the WR at LAT. MRT and  $\tau$  were longer in the transitions from prior exercise than from rest. This study has shown  $\text{VO}_2$  kinetics to be delayed when a given increment in WR occurred from prior exercise, whether the final WR was below or above the LAT. The data were modeled using a single-component exponential function that incorporated a  $T_D$  and one that did not incorporate a  $T_D$ . The mono-exponential model with a  $T_D$  was used to fit the data for time ( $T$ ) > 15 s. All data points were fit from the second exercise sample point ( $T > 15$  s) to the 10-min point. By ignoring this initial rapid increase in  $\text{VO}_2$  due to the rapid return of pooled venous blood ( $T < 15$  s), they attempted to describe the kinetics of  $\text{VO}_2$  response to the exercise task itself. There were individual differences in the kinetic response pattern at the onset of exercise. A single-component exponential model without a  $T_D$ , was also fit to both the data for  $T > 0$  s and  $T > 15$  s, yet the fit was not as good as the model that incorporated a  $T_D$ .

#### $\text{VO}_2$ Response Profile in Severe Intensity Exercise

Poole, Ward, and Whipp (1990) hypothesized that the heavy and severe exercise domains were demarcated by CP. It is within this domain that  $\text{VO}_2$  cannot be stabilized, and continues to rise until fatigue sets in and  $\text{VO}_2$  reaches a maximal level (Gaesser & Poole, 1996; Poole et al.). As in heavy exercise, there is an appearance of the slow component, which drives  $\text{VO}_2$  above the predicted value.

There is no agreement as to whether the slow component is best described as an exponential or linear increase. It is possible that the  $\text{VO}_2$  slow component may be a combination of the two, or may even look quite different (Gaesser & Poole, 1996).

Casaburi, Barstow, Robinson, and Wasserman (1989) tested 4 participants on a cycle ergometer for a total of 162 tests at seven different WR's. Intensities for each participant resulted in three WR's below the LAT and three above the LAT. One other WR was below LAT for three of the four participants, but above the LAT for one participant. Three mathematical models were fit to the data. The first and simplest was a mono-exponential model fit to the data from the time at which WR was increased from unloaded pedaling through min 7 of exercise. The  $\tau$  was the only parameter evaluated. The second model omitted the Phase I period from the data fit and incorporated both an exponential component and a  $T_D$ . Casaburi et al. also sought to determine whether a slower exponential component was present by fitting each data set to a third model, which was the sum of two exponential components. For the second and third models, the Phase I response was excluded. Kinetics were consistently better fit by a double-exponential model at WR's associated with an elevated blood lactate. The contribution of the slower response component tended to increase with increasing WR and the  $\tau$  tended to become longer. The mean  $\tau$  at the lowest WR was 32.2 s and the mean  $\tau$  at the highest WR was 68.9 s. The  $\text{VO}_2$  response below the LAT tended to be better fit by models featuring a mono-exponential plus a  $T_D$  and were sometimes associated with an additional small upward slope. The MRT ( $\tau$  for the mono-exponential model,  $\tau + T_D$  for the mono-exponential model with a  $T_D$ ) for each model did not differ substantially, and

therefore, it can be reasonably well approximated by the simpler procedure of fitting a single  $\tau$  to the response data. It was found that kinetics showed a mild dependence on WR at intensities below the LAT (i.e., moderate intensity exercise). The kinetics at high WR's are well characterized by the addition of a slower exponential component to the faster component that is seen in lower WR's. Although not explicitly stated, examination of their data suggests that each participant had, at most, only one test in the severe domain. Thus, the implication is that kinetics are slower in heavy than moderate, and slower still in severe than heavy, but no conclusions can be drawn regarding the effect of intensity with the severe domain.

Barstow and Molé (1991) tested 4 trained cyclists during transitions from 33 W to WR's throughout all three domains (38, 54, 85, and 100% of  $\text{VO}_{2\text{max}}$ ). In every case, three phases (Phases I, II, and III) of the  $\text{VO}_2$  response could be identified.  $\text{VO}_2$  during Phase II was fit by one of two models: (1) a double-exponential where both terms begin together close to the start of Phase II, and (2) a double-exponential where each of the exponential terms begins independently with separate  $T_D$ 's. For the two lighter WR's, the double-exponential regression reduced to a single value for  $\tau$ , indicating a mono-exponential response. For the heaviest WR's, the second model produced a significantly better fit to the responses with a mean  $T_D$  for the slow component of  $105 \pm 46$  s. The time constant of the fast component exhibited no significant change as WR increased. This better fit of the second model to the responses implies that the second component does not begin coincident with the first, i.e., soon after exercise onset, but rather, later into the exercise period.



Pulmonary gas exchange responses within the severe domain have been less well characterized than those within the moderate and heavy domains. Thus there is no consensus on the actual modeling of the slow component within this exercise domain.

#### Effect of Intensity on Kinetics within the Severe Domain

Whipp (1994) has stated that  $T_{VO_{2max}}$  is shorter ( $VO_{2max}$  is achieved faster) at higher intensities and, by definition, these intensities must fall within the severe domain. In two recent studies evaluating responses in the severe intensity domain, it was reported that  $T_{VO_{2max}}$  is faster at higher intensities for both running (Hill & Ferguson, 1999) and cycle ergometer exercise (Hill & Smith, 1999).

Hill and Ferguson (1999) examined the effect of velocity on the rate of response over a narrow range of intensities above the LAT. Twelve individuals performed exhaustive runs at 95% to 110% of the velocity at which  $VO_{2max}$  was attained in an incremental test. The  $T_{fat}$  was shorter at higher velocities, and  $VO_{2max}$  was always achieved faster at higher velocities.  $T_{VO_{2max}}$  in this study was estimated as the time from the onset of exercise until a 15-s  $VO_2$  equaled or exceeded the highest 30-s  $VO_2$  in the test. Results showed that  $T_{fat}$ ,  $T_{VO_{2max}}$ , and the time that  $VO_{2max}$  was sustained were longer in lower velocity tests.

Hill and Smith (1999) evaluated the relationship between intensity and  $T_{VO_{2max}}$  in cycle ergometer exercise. Eight participants each completed 3 exhaustive cycle ergometer tests within the severe domain. The mean ( $\pm$  SD) power outputs for the predicting trials were  $328 \pm 86$  W,  $256 \pm 70$  W, and  $198 \pm 43$  W, and  $T_{fat}$  were  $85 \pm 11$  s,  $171 \pm 68$  s, and  $522 \pm 189$  s, respectively.  $T_{VO_{2max}}$ , calculated as above, were  $67 \pm 15$  s,  $140 \pm 69$  s, and

352±04 s. These findings support the work of Hill and Ferguson (1999) that there is a faster response at higher exercise intensities.

Although the preceding studies evaluated  $\text{VO}_2$  responses by examining  $T_{\text{VO}_{2\text{max}}}$  and  $T_{\text{fat}}$ , and suggest a faster response at higher intensities, these  $T_{\text{VO}_{2\text{max}}}$  values may provide a somewhat crude description of the response. However, by fitting a mathematical model to the data, it is possible to compare response times and examine the relationship between intensity and kinetic responses within the severe domain.

Hill, Williams, and Burt (1997) tested 6 male participants at the velocity associated with  $\text{VO}_{2\text{max}}$  and at 92% of the velocity associated with  $\text{VO}_{2\text{max}}$ . At the velocity associated with  $\text{VO}_{2\text{max}}$ ,  $\text{VO}_{2\text{max}}$  was reached after  $299 \pm 74$  s. At 92% of the velocity associated with  $\text{VO}_{2\text{max}}$ , a longer time period was required to attain  $\text{VO}_{2\text{max}}$  ( $491 \pm 156$  s). The kinetics of the  $\text{VO}_2$  response were described using a mono-exponential model. Results showed a faster response (i.e., smaller  $\tau$ ) at the higher velocity. The  $\tau$  of the response at the velocity associated with  $\text{VO}_{2\text{max}}$  was 33 s, while the response was slower ( $\tau = 38$  s) at the lower velocity.

Hill, Poole, and Smith (1999) described a relationship between WR and  $\text{VO}_2$  kinetics over a range of intensities within the severe domain, with  $\tau$  being faster at higher WR's. Eleven participants completed exhaustive cycle ergometer tests at WR's that spanned the severe domain. The data did not fit a two-component model. Therefore, the data were forced to fit a mono-exponential response. The rapidity of the  $\text{VO}_2$  response increased systematically at higher WR's. Participants exercised at 95, 100, 110, and

135% of the highest power output that could be sustained for 1 min in his/her incremental test, and  $\tau$ 's were  $52 \pm 33$  s,  $47 \pm 11$  s,  $37 \pm 9$  s, and  $27 \pm 4$  s, respectively.

In a recent study that evaluated kinetics during exercise at similar intensities, Hughson, Betik, O'Leary, and Hebestreit (1998) reported that the time constant of the  $\text{VO}_2$  response was faster at 130% of  $\text{VO}_{2\text{max}}$  than at 100% of  $\text{VO}_{2\text{max}}$ . Eight participants exercised at 50, 100, and 130% of  $\text{VO}_{2\text{max}}$ . Data were then fit by a two- or three-component exponential models. The  $\tau$ , which reflected the rate of adaptation after the first 15 s of exercise, was 16.3 s for exercise at 130% of  $\text{VO}_{2\text{max}}$  versus 22.1 s for exercise at 100% of  $\text{VO}_{2\text{max}}$ .

In summary, kinetics are slower at higher intensities when comparing above LAT to below LAT intensities. But the limited evidence suggests that, within severe intensities,  $\tau$  is faster as intensity increases. Thus, the purposes of this study were to examine the effect of intensity on the kinetic responses within the severe domain and to describe mathematically the  $\text{VO}_2$  kinetics during cycle ergometry.

## CHAPTER 3

### METHODS

The purpose of this investigation was to characterize better the oxygen uptake ( $\text{VO}_2$ ) response within the severe intensity domain. This chapter will explain how the research was conducted, how parameters were calculated, and how the data were analyzed.

#### Participants

Sixteen participants (8 men, 8 women) were recruited from undergraduate exercise physiology courses to participate in this study which was approved by the Institutional Review Board at the University of North Texas. The participants were involved in personal fitness activities, but none was training for competitive sport. Participant demographics are presented in chapter four. The participants received partial course credit for their participation in the study. All participants were screened to meet American College of Sports Medicine Guidelines for individuals who do not require a medical exam and physician supervised exercise test prior to participation. All participants provided a voluntary written consent (Appendix A) prior to data collection and completed a standard medical history form. Each participant's resting heart rate, blood pressure, and 12-lead electrocardiogram (EKG) were evaluated for exclusion criteria namely tachycardia, blood pressure  $>150/100$ , or obvious EKG abnormality.

#### Overview

Each participant reported to the lab on 9–13 occasions. On the initial visit, screening was performed and paperwork completed. Participants were instructed to

standardize dietary intake and limit physical activity in the 24 h prior to testing.

Compliance was verified before each test. Each participant's age, height, and weight were recorded prior to each test.

Each participant completed a total of 8-12 exhaustive tests, each performed on an electronically-braked Ergoline 800s cycle ergometer (Mijnhart 800S, the Netherlands) which provided a constant work rate (WR) independent of pedal cadence. All tests were separated by at least 24 h, and were given at approximately the same time each day in a temperature-controlled laboratory (20 to 22 °C). The first test followed an incremental protocol and was used to determine maximal  $\text{VO}_2$  ( $\text{VO}_{2\text{max}}$ ). A constant power protocol was followed during the remaining tests, the first two of which were used as practice trials and were not included in statistical analyses. After completing the practice trials, each participant performed 7-11 constant power tests (one test/day) at different intensities within the severe intensity domain.  $\text{VO}_2$  kinetics were determined for each of these tests.

During each test and the warm-up that preceded it, expired gases were collected and analyzed on a breath-by-breath basis by a CPX metabolic cart (Medical Graphics Inc., St. Paul, MN). Prior to each test, the  $\text{O}_2$  and  $\text{CO}_2$  analyzers were calibrated according to the manufacturer's instructions using gases of known concentration, and the pneumotach was calibrated using a standard 3-liter syringe. Heart rate was monitored using a Polar Edge heart rate monitor (Polar CIC Inc., Port Washington, NY).

In all tests, pedal cadence was at the participant's discretion, and participants received strong verbal encouragement to continue pedaling as long as possible. The tests were terminated when the subject could no longer maintain a cadence of at least 60

rev·min<sup>-1</sup>. If the cadence fell below this for less than 3 s, and the participant could recover back to 60 rev·min<sup>-1</sup>, the test continued. Participants were not aware of their elapsed time during any of the tests, nor were they informed of the results of any trial until all trials had been completed.

#### Determination of VO<sub>2max</sub>

All participants performed an incremental cycle ergometer test in order to determine VO<sub>2max</sub>. The initial WR was set at 50 watts for both men and women. All stages were 1 min in duration, and the WR was increased by 25 watts for men and 20 watts for women at the end of each stage. Incremental tests were performed to exhaustion. From the breath-by-breath data, VO<sub>2max</sub> was determined as the highest 30-s rolling average of 15-s serial samples and as the highest 30-breath rolling average.

#### Constant Power Tests

Participants performed constant power tests at WR's selected to elicit fatigue in times ranging from 3 to 10 min. The initial WR was chosen as the highest WR that the participant could sustain for 1 min in the incremental test. Subsequent WR's were selected by trial and error. The first two of the constant power trials served as practice trials. The only exception was one very fit participant for whom performance in one "practice" test was clearly worthy and therefore included in the analyses. All of the constant power tests began with a 5-min warm-up at a WR adjusted to elicit a heart rate between 120 and 140 b·min<sup>-1</sup>. Following the warm-up, participants sat on the cycle ergometer and rested for 5 min. Upon completion of the 5-min recovery period, participants pedaled against zero resistance for two pedal strokes before the resistance

was applied. Participants exercised to fatigue, and time to fatigue ( $T_{fat}$ ) was measured to the nearest second. Gas exchange data were collected continuously throughout the tests.

### Determination of Kinetics

For each participant, for each test, the breath-by-breath data were fit by KaleidaGraph™ data analysis/graphing application (Reading, PA) to a series of models. All of the models are presented in Appendix B, and three are described here.

One model (model 1) was the simple mono-exponential with no time delay ( $T_D$ ),

$$VO_2(T) = VO_{2baseline} + (VO_{2fastgain} \cdot (1 - e^{(-T/\tau)}))$$

where  $VO_2(T)$  is the value for  $VO_2$  at time =  $T$ ,  $VO_{2baseline}$  is the average  $VO_2$  in the 2 min before exercise,  $VO_{2fastgain}$  is the projected increase in  $VO_2$  above the baseline, and the  $\tau$  is a parameter that provides a measure of the rate of response. The value of  $\tau$  is typically about 45 s (Whipp et al., 1982).

A second model (model 5) included a fast exponential response along with a delayed slow component,

$$VO_2(T) = VO_{2baseline} + (VO_{2fastgain} \cdot (1 - e^{(-T/\tau_1)})) + (VO_{2slowgain} \cdot (1 - e^{(-(T - T_{D2})/\tau_2)}))$$

where the second, slow component occurs in addition to the rapid response described in the first model. The  $VO_{2slowgain}$  is the projected excess  $VO_2$  above the projected  $VO_{2fastgain}$ . The slow gain is manifest only after a delay ( $T_{D2}$ ), which typically has a value of about 2 min. The rapid initial response continues throughout the exercise bout (although the projected gain is essentially attained after about 3 min or, more precisely, 99% of the fast gain is achieved after  $T = 4.6 \cdot \tau_1$ ). The slow gain has been reported to be

as large as 1000 ml·min<sup>-1</sup>, although values are more typically about 300 ml·min<sup>-1</sup> (Gaesser & Poole, 1996).

A third model (model 8), similar to the second, also included a fast and slow component. In this model, there was no  $T_D$  term, with both components beginning at the onset of exercise. The response was described by

$$VO_2(T) = VO_{2\text{baseline}} + (VO_{2\text{fastgain}} \cdot (1 - e^{(-T/\tau_1)})) + (VO_{2\text{slowgain}} \cdot (1 - e^{(-T/\tau_2)})).$$

### Statistical Analysis

First, in order to determine if constant power tests were at WR's that fell within the severe domain, the mean 30-breath  $VO_{2\text{max}}$  from the incremental test was compared to the mean 30-breath  $VO_{2\text{max}}$  from the constant power tests using a paired samples t-test.

As noted above, kinetics parameters were derived using KaleidaGraph™ data analysis/graphing application. For each parameter estimate, a *SE* was also generated. A model was judged to have an “excellent” fit to the data for a given participant for a given test if the *SE* of every parameter estimate was less than or equal to 20% of the estimate. A model was judged to have a “good” fit to the data for a given participant for a given test if the *SE* of every parameter estimate was less than or equal to 50% of the estimate.

It was determined that a model accurately described the  $VO_2$  response if at least a “good” fit was obtained in at least 20% of tests. In order to evaluate the influence of test duration (or test intensity) on the  $VO_2$  profile, tests were grouped according to  $T_{\text{fat}}$  (120-239 s, 240-359 s, 360-479 s, and  $\geq 480$  s) and the percentage of times a particular model “worked” and produced a “good” or “excellent” fit in each grouping was calculated. The correlation between WR and  $\tau$  derived using the simple mono-exponential model, was



calculated for each individual separately and for the group as a whole. Correlations were calculated using *SPSS* 10 (Chicago, IL). Using the parameters described by the best-fit model, a correlation was run between  $\tau$  and  $T_{\text{fat}}$  for the group and each individual.

In addition, to describe kinetic responses to high and low intensity tests within the severe domain, a mean  $\tau$  was calculated for each participant's longest test and a mean  $\tau$  was calculated for the shortest tests. These means were compared using a paired means t-test.

For all analyses, a  $p$  level of  $\leq .05$  was used to denote statistical significance.

## CHAPTER 4

### RESULTS

The primary purpose of this study was to describe mathematically the oxygen uptake ( $\text{VO}_2$ ) kinetics during cycle ergometer exercise within the severe intensity domain. A secondary purpose was to examine the effect of intensity on the kinetic responses within the severe domain. The results from this study are presented in this chapter.

Demographic data are presented in Table 1. The mean 30-breath maximal  $\text{VO}_2$  ( $\text{VO}_{2\text{max}}$ ) value in incremental tests was  $2810 \pm 750 \text{ ml} \cdot \text{min}^{-1}$  ( $39.3 \pm 6.6 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ). Due to technical problems, an incremental  $\text{VO}_{2\text{max}}$  value was not available for 1 participant. With these 15 participants contributing one value (the mean of his or her 30-breath  $\text{VO}_{2\text{max}}$  from all constant power tests), the group mean  $\text{VO}_{2\text{max}}$  in constant power tests was  $2726 \pm 681 \text{ ml} \cdot \text{min}^{-1}$  ( $38.5 \pm 5.7 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ), which was 97% of the incremental mean value ( $t_{14} = 2.36, p = .03$ ). The incremental and constant power means were highly correlated ( $r = 0.99, p < .01$ ).

The goal was for time to fatigue ( $T_{\text{fat}}$ ) in the constant power exercise tests to be no greater than 10-12 min. Therefore, data from two tests, in which  $T_{\text{fat}}$  was  $\sim 15$  min and  $\sim 20$  min, were not used. In addition, for one participant, in one test, the rate of response ( $\tau$ ) was  $> 200$  s. This was over 13  $SD$ 's larger than the group mean value ( $47.8 \pm 13.6$  s); therefore, this outlier was not included in analyses. Data from the remaining 76 tests were analyzed.

Table 1

Participant Demographics

	Male ( $n = 8$ )	Female ( $n = 8$ )
Age	$22 \pm 2$	$21 \pm 2$
Height (cm)	$181.8 \pm 4.5$	$170.0 \pm 5.1$
Weight (kg)	$81.5 \pm 7.9$	$62.9 \pm 7.7$
VO <sub>2max</sub> <sup>*</sup> (ml·min <sup>-1</sup> )	$3518 \pm 269$	$2191 \pm 353$

Note. Values are  $M \pm SD$ . <sup>\*</sup>Value from incremental tests ( $n = 7$  for the male subgroup).

The first working hypothesis was that the VO<sub>2</sub> response profile for exercise at all intensities within the severe domain would be well described by one-component models. Of the two one-component models used, only model 1, which featured a mono-exponential increase with no T<sub>D</sub>, provided a “good” fit (i.e., each *SE* was < 50% of each parameter estimate) across intensities. In fact, there was an “excellent” fit (all *SE* ≤ 20% of the parameter estimate) in 97% of the tests. Results are presented in Table 2.

The second hypothesis was that a slow component would be present only at lower intensities within the severe domain. Specifically, it was hypothesized that models that include two components would adequately describe responses only in longer tests (i.e., lower intensities) within this domain. In order to evaluate the influence of test duration (or test intensity) on the VO<sub>2</sub> profile, tests were grouped according to T<sub>fat</sub> (< 240 s, 240-359 s, 360-479 s, and ≥480 s) and calculated the % of times a particular model “worked”

in each grouping. Two two-component models consistently provided a good fit. Model 5 provided a good fit in only 10 of the 64 tests (16%) that were < 8 min, but in 9 of 12 tests (75%) that were 8 min or longer. Similarly, model 8 provided a good fit in only 13 of the 64 tests (20%) that were < 8 min, but in 8 of the 12 tests (67%) that were 8 min or longer. Results are presented in Table 3.

Table 2

Goodness of Fit for All Models

Model	N	<u>SE as a percentage of parameter estimate</u>			
		Excellent <20	Good 20-50	Poor 50-100	Very poor >100
1	76	74 (97)	2 (3)		
2	76	1 (1)	5 (7)	2 (3)	68 (89)
3	76		3 (4)	12 (16)	61 (80)
4	76		4 (5)	9 (12)	63 (83)
5	76	4 (5)	15 (20)	12 (16)	45 (59)
6	76		2 (3)	2 (3)	72 (94)
7	76		3 (4)	4 (5)	69 (91)
8	76	4 (5)	17 (22)	9 (12)	46 (61)
9	76	4 (5)	3 (4)	7 (9)	62 (82)

Note. Values are the number of tests meeting each criterion for goodness of fit, with the percentage value in parentheses.

Table 3

Goodness of Model Fit by Duration

Model	duration (s)	<i>n</i>	<u>SE as a percentage of the parameter estimate</u>			
			Excellent <20	Good 20-50	Poor 50-100	Very poor >100
1	< 240	24	24 (100)			
	240 – 359	27	26 (96)	1 (4)		
	360 – 479	13	12 (92)	1 (8)		
	≥ 480	12	12 (100)			
5	< 240	24		1 (4)	3 (13)	20 (83)
	240 – 359	27	1 (4)	4 (15)	5 (19)	17 (63)
	360 – 479	13	1 (8)	3 (23)	3 (23)	6 (46)
	≥ 480	12	2 (17)	7 (58)	1 (8)	2 (17)
8	< 240	24			3 (13)	21 (87)
	240 – 359	27	1 (4)	8 (30)	3 (11)	15 (55)
	360 – 479	13	1 (8)	3 (23)	2 (15)	7 (54)
	≥ 480	12	2 (17)	6 (50)	1 (8)	3 (25)

Note. Values are the number of tests meeting each criterion for goodness of fit, with the percentage value in parentheses.

The third hypothesis was that response kinetics would be faster at higher intensities. Specifically, it was hypothesized that there would be a significant negative relationship between  $\tau$  and work rate (WR). Also with respect to this hypothesis, it was proposed that there would be a significant positive correlation between  $\tau$  and  $T_{\text{fat}}$ . On average, for the 16 participants, the correlation between  $\tau$  and WR was -.80, and the relationship between  $\tau$  and WR was  $\tau = 147 \text{ s} - (.409 \text{ s} \cdot \text{W}^{-1} \cdot \text{WR})$  (Appendix C). When data from all 76 tests were analyzed together, there was not a significant correlation between  $\tau$  and WR, and therefore, no regression analysis was performed on these group data.

Also regarding the third hypothesis, on average, for the 16 participants, the correlation between  $\tau$  and  $T_{\text{fat}}$  was 0.77, and regression analyses revealed  $\tau = 24.2 \text{ s} + (0.075 \text{ s} \cdot \text{s}^{-1} \cdot T_{\text{fat}})$ . When data from all 76 tests were analyzed together, there was a significant correlation between  $\tau$  and  $T_{\text{fat}}$  ( $r = 0.61, p < .001$ ). The relationship was  $\tau = 28.1 \text{ s} + (0.061 \text{ s} \cdot \text{s}^{-1} \cdot T_{\text{fat}})$  (Appendix D). The y-intercept of 28.1 s was significantly different from zero ( $t_{74} = 8.53, p < .001$ ) and was associated with a *SE* of 3.3. The slope of .061 was significantly different from zero ( $t_{74} = 8.56, p < .001$ ) and was associated with a *SE* of .009.

Finally, consistent with the negative correlation between  $\tau$  and WR, mean  $\tau$  in the 16 participants' highest intensity test ( $37.1 \pm 7.7 \text{ s}$ ) was faster than in their lowest intensity test ( $60.0 \pm 14.1 \text{ s}, t_{15} = -8.14, p < .001$ ).

In summary, a mono-exponential model with no  $T_D$  (model 1) described the response across all intensities. Two-component models (models 5 and 8) worked well in tests with  $T_{fat} > 8$  min. Based on the  $\tau$  from model 1, the  $VO_2$  response was faster at higher intensities and directly related to  $T_{fat}$ .

## CHAPTER 5

### DISCUSSION

The primary purpose of this study was to describe mathematically the oxygen uptake ( $\text{VO}_2$ ) kinetics during cycle ergometry within the severe intensity domain. A secondary purpose was to examine the effect of intensity on the kinetic responses within the severe domain.

By definition, maximal  $\text{VO}_2$  ( $\text{VO}_{2\text{max}}$ ) is achieved during fatiguing exercise at intensities within the severe domain. However,  $\text{VO}_{2\text{max}}$  may or may not be achieved *because of* a slow component to the response. That is, there may be two distinct  $\text{VO}_2$  profiles within the severe exercise intensity domain. Gaesser and Poole (1996) have discussed that  $\text{VO}_{2\text{max}}$  can be reached during exercise in the severe domain *because of* (italics mine) a slow component in the  $\text{VO}_2$  response. However, Whipp (1994, p 1322) has noted that a slow component cannot be detected in “constant-load tests in which the subject reaches the maximum  $\text{VO}_2$  in a few minutes.” In the present investigation, the  $\text{VO}_2$  response at all intensities was well described by a mono-exponential model. However, responses in the longest tests ( $\geq 8$  min) were also described well by two models (model 5 and model 8) that included a slow component. A slow component was present only at lower intensities within the severe domain. Specifically, models that included two components adequately described responses only in longer tests within this domain.

When all breath-by-breath data were used to quantify the  $\text{VO}_2$  kinetics, rate of response ( $\tau$ ) was smaller (the response faster) at the higher work rates (WR's) within the severe intensity domain. The influence of intensity on kinetics is in agreement with the



assertions of Whipp (1994), as well as the results of several studies (Hughson et. al, 1998; Hill & Ferguson, 1999; Hill & Smith, 1999; Hill et. al, 1999), that  $\text{VO}_{2\text{max}}$  is achieved faster at higher intensities. In two studies evaluating responses in the severe intensity domain, the time to achieve  $\text{VO}_{2\text{max}}$  ( $T_{\text{VO}_{2\text{max}}}$ ) was found to be faster at higher intensities for both treadmill running (Hill & Ferguson) and cycle ergometer exercise (Hill & Smith). Hughson et al. also reported that the rate of increase in  $\text{VO}_2$  after the first 15 s of exercise was faster at 130% of  $\text{VO}_{2\text{max}}$  than at 100% of  $\text{VO}_{2\text{max}}$ . Whipp (1994) stated that  $T_{\text{VO}_{2\text{max}}}$  is shorter ( $\text{VO}_{2\text{max}}$  is achieved faster) at higher intensities. Hill et al. described a relationship between WR and  $\text{VO}_2$  kinetics over a range of intensities within the severe domain, with mean response time faster at higher WR's.

The faster response at higher exercise intensities suggests that the kinetics of the  $\text{VO}_2$  response may be driven by the  $\text{O}_2$  demand and not by the final  $\text{VO}_2$ , since only the  $\text{O}_2$  demand differed from WR to WR. Whipp (1994) has asserted that the metabolic demand is the driving force behind  $\text{VO}_2$  kinetics, even if it is not exactly clear how the demand is quantified.

Previous studies have not identified the mechanism responsible for the slow component seen during exercise at intensities above the lactate threshold. Purported mechanisms include the effects of lactate, epinephrine, cardiac and ventilatory work, temperature, potassium, less efficient mitochondrial P-O coupling, reduced chemical-mechanical coupling efficiency, and recruitments of lower-efficiency fast-twitch motor units (Gaesser & Poole, 1996). Current evidence suggests that the primary origin of the slow component appears to be in the working limbs (Gaesser & Poole; Poole et al.,

1991). The results of this study cannot give information about what is responsible for the slow component. However, two things are clear. First, the slow component is not present – or at least is not quantifiable based on description of  $\text{VO}_2$  kinetics – in shorter (higher intensity) tests. Second, the slow component does not drive the  $\text{VO}_2$  to values above  $\text{VO}_{2\text{max}}$ . Consistent with Sloniger et al. (1996), the  $\text{VO}_2$  achieved in the longer tests was not consistently higher than the  $\text{VO}_2$  achieved in shorter constant power tests or in the incremental tests.

In summary, the primary purpose of this study was to describe mathematically the  $\text{VO}_2$  kinetics during cycle ergometry within the severe intensity domain. A mono-exponential model with no time delay (model 1) described the response across all intensities. However, two-component models (models 5 and 8) worked well in tests with time to fatigue ( $T_{\text{fat}}$ ) > 8 min, showing that there is a slow component at lower intensities within severe intensity domain. A secondary purpose was to examine the effect of intensity on the kinetic responses within the severe domain. Based on the  $\tau$  from model 1, the  $\text{VO}_2$  response was faster at higher intensities and directly related to  $T_{\text{fat}}$ .

APPENDIX A  
PARTICIPANT INFORMED CONSENT

UNIVERSITY OF NORTH TEXAS  
DEPARTMENT OF KINESIOLOGY, HEALTH PROMOTION, AND RECREATION

CONSENT TO ACT AS A HUMAN SUBJECT

Subject's Name(print): \_\_\_\_\_ Date: \_\_\_\_\_

1. I hereby volunteer to participate as a subject in laboratory testing. I understand that this testing is part of a study titled "Defining the severe exercise intensity domain." The purpose of this study is to use mathematical modeling of responses to cycle ergometer exercise in order to predict the lowest and highest exercise intensities that will elicit a maximal aerobic response.

I hereby authorize David W. Hill and/or assistants as may be selected by him to perform on me the following procedures, on different days:

(a) to have me pedal on a cycle ergometer for 1 minute at a submaximal intensity (50 watts); to have me continue to pedal until I feel I cannot continue while the work rate is increased slightly (20 watts for women, 25 watts for men) each minute;

[I understand that this test will last approximately 8 to 12 minutes, depending upon my fitness level];

(b) to have me pedal at a fixed work rate on a cycle ergometer until I feel I cannot continue (12 times, once per day on 12 different days);

[I understand that it is up to me to try to continue as long as I can, and that the tests are at different work rates and they will last approximately 1 minute to 12 minutes];

I understand that during all exercise tests I will be breathing through a mouthpiece and that my nose will be pinched shut.

2. The procedures outlined in paragraph 1 [(a) and (b), above] have been explained to me by David W. Hill.

3. I understand that the procedures involve the following risks and discomforts: temporary muscle pain is expected during exercise, and nausea and lightheadedness is common after exercise; there is the possibility of abnormal changes in my heart beat or blood pressure or even of a heart attack during the tests. However, I understand that heart rate, blood pressure, and EKG will be taken before testing, that my cardiovascular and metabolic responses to exercise will be monitored throughout all tests, and that I can terminate any test at any time at my discretion.

4. I have been advised that the following benefits will be derived from my participation in this study: aside from learning about my aerobic and anaerobic fitness level, there are no direct benefits to me.
5. I understand that David W. Hill and/or appropriate assistants as may be selected by him will answer any inquiries that I may have at any time concerning these procedures and/or investigations.
6. I understand that all data concerning myself will be kept confidential and available only upon my written request. I further understand that in the event of publication, no association will be made between the reported data and myself.
7. I understand that there is no monetary compensation for my participation in this study.
8. I understand that, in the event of physical injury directly resulting from participation in this study, compensation cannot be provided. Medical treatment will be available at the University Health Center for UNT students; the laboratory has an outside telephone line to contact emergency medical services (911).
9. I understand that I may terminate participation in this study at any time without prejudice to future care or any possible reimbursement of expenses, compensation, employment status, or course grade, and that, owing to the scientific nature of the study, the investigator may terminate the procedures and/or investigation at any time.
10. I understand that I may contact the chairperson of the KHPR Committee on the Use of Human Subjects, Dr. Noreen Goggin (PEB 112, 940-565-2212) on any matters concerning my participation in this study if I feel that there is infringement on my rights.

Subject's Signature: \_\_\_\_\_

Witness: \_\_\_\_\_ Date: \_\_\_\_\_

This project has been reviewed by the University of North Texas  
Institutional Review Board  
for the Protection of Human Subjects in Research  
(940-565-3940)

APPENDIX B  
MATHEMATICAL MODELS

### Model 1

$$VO_2(T) = VO_{2baseline} + (VO_{2fastgain} \cdot (1 - e^{(-T/\tau_1)}))$$

$$m1+m2*((m0 \leq 0)?0:(1-\exp(-m0/m3))); m1=700; m2=1400; m3=25$$

### Model 2

$$VO_2(T) = VO_{2baseline} + (VO_{2fastgain} \cdot (1 - e^{(-(T - T_{D1})/\tau_1)}))$$

$$m1+m2*((m0 \leq m3)?0:(1-\exp(-(m0-m3)/m4))); m1=700; m2=1400; m3=5.0; m4=25$$

$$1$$

$$\exp((m0-m3)*(m0-m3)/(m4*m4))$$

$$-2*((m0-m3)/(m4*m4))*m2*\exp((m0-m3)*(m0-m3)/(m4*m4))$$

$$-2*((m0-m3)*(m0-m3)/(m4*m4*m4))*m2*\exp((m0-m3)*(m0-m3)/(m4*m4))$$

### Model 3

$$VO_2(T) = VO_{2baseline} + (VO_{2cardiogain} \cdot (1 - e^{(-T/\tau_{cardio})})) + (VO_{2fastgain} \cdot (1 - e^{(-(T - T_{D1})/\tau_1)}))$$

- No further increase in  $VO_2$  is attributable to the cardiodynamic gain after  $T = T_{D1}$  so it's first the cardiodynamic response (then the Phase I rapid exponential response)

$$m1+m2*((m0 \leq 0)?0:((m0 \leq m5)?(1-\exp(-m0/m3)):(1-\exp(-m5/m3))))+m4*((m0 \leq m5)?0:(1-\exp(-(m0-m5)/m6))); m1=500; m2=500; m3=10; m4=2000; m5=20; m6=25$$

### Model 4

$$VO_2(T) = VO_{2baseline} + (VO_{2cardiogain} \cdot (1 - e^{(-T/\tau_{cardio})})) + (VO_{2fastgain} \cdot (1 - e^{(-(T - T_{D1})/\tau_1)}))$$

- After  $T = T_{D1}$  the Phase I rapid response begins and is additive to the cardiodynamic effect which continues to contribute.

$$m1+m2*((m0 \leq 0)?0:(1-\exp(-m0/m3)))+m4*((m0 \leq m5)?0:(1-\exp(-(m0-m5)/m6))); m1=500; m2=300; m3=5; m4=1500; m5=15; m6=25$$

## Model 5

$$VO_2(T) = VO_{2baseline} + (VO_{2fastgain} \cdot (1 - e^{-(T - TD2) / \tau_1})) + (VO_{2slowgain} \cdot (1 - e^{-(T - TD2) / \tau_2}))$$

$$m1 + m2 * ((m0 \leq 0) ? 0 : (1 - \exp(-m0/m3))) + m4 * ((m0 \leq m5) ? 0 : (1 - \exp(-(m0 - m5)/m6))); m1=500; m2=2000; m3=25; m4=500; m5=120; m6=120$$

## Model 6

$$VO_2(T) = VO_{2baseline} + (VO_{2cardiogain} \cdot (1 - e^{-(T / \tau_{cardio})})) + (VO_{2fastgain} \cdot (1 - e^{-(T / \tau_1)})) + (VO_{2slowgain} \cdot (1 - e^{-(T - TD2) / \tau_2}))$$

- cardiodynamic response ends when the fast response begins (at  $T = T_{D1}$ )
- rapid response continues throughout exercise (after  $T = T_{D1}$ )
- the slow component Phase III response begins at  $T = T_{D1}$  and continues throughout the exercise

$$m1 + m2 * ((m0 \leq 0) ? 0 : ((m0 \leq m5) ? (1 - \exp(-m0/m3)) : (1 - \exp(-(m5 - m0)/m3)))) + m4 * ((m0 \leq m5) ? 0 : (1 - \exp(-(m0 - m5)/m6))) + m7 * ((m0 \leq m8) ? 0 : (1 - \exp(-(m0 - m8)/m9))); m1=500; m2=500; m3=5; m4=2000; m5=20; m6=50; m7=500; m8=150; m9=200$$

## Model 7

$$VO_2(T) = VO_{2baseline} + (VO_{2cardiogain} \cdot (1 - e^{-(T / \tau_{cardio})})) + (VO_{2fastgain} \cdot (1 - e^{-(T / \tau_1)})) + (VO_{2slowgain} \cdot (1 - e^{-(T - TD1) / \tau_2}))$$

- cardiodynamic response ends at  $T = T_{D1}$
- rapid response (Phase II) and slow response (Phase III) both begin at  $T = T_{D1}$  and
- continue throughout the exercise

$$m1 + m2 * ((m0 \leq 0) ? 0 : ((m0 \leq m5) ? (1 - \exp(-m0/m3)) : (1 - \exp(-(m5 - m0)/m3)))) + m4 * ((m0 \leq m5) ? 0 : (1 - \exp(-(m0 - m5)/m6))) + m7 * ((m0 \leq m5) ? 0 : (1 - \exp(-(m0 - m5)/m8))); m1=500; m2=500; m3=10; m4=2000; m5=20; m6=25; m7=500; m8=200$$



### Model 8

$$VO_2(T) = VO_{2baseline} + (VO_{2fastgain} \cdot (1 - e^{(-T/\tau_1)})) + (VO_{2slowgain} \cdot (1 - e^{(-T/\tau_2)}))$$

$$m1+m2*((m0 \leq 0)?0:(1-\exp(-m0/m3)))+m4*((m0 \leq 0)?0:(1-\exp(-m0/m6))); m1=500; m2=2000; m3=25; m4=500; m6=120$$

### Model 9

$$VO_2(T) = VO_{2baseline} + (VO_{2fastgain} \cdot (1 - e^{(-T/\tau_1)})) + (VO_{2slow\_linear\_gain} \cdot ((T - T_{D2}) / (T_{D3} - T_{D2})))$$

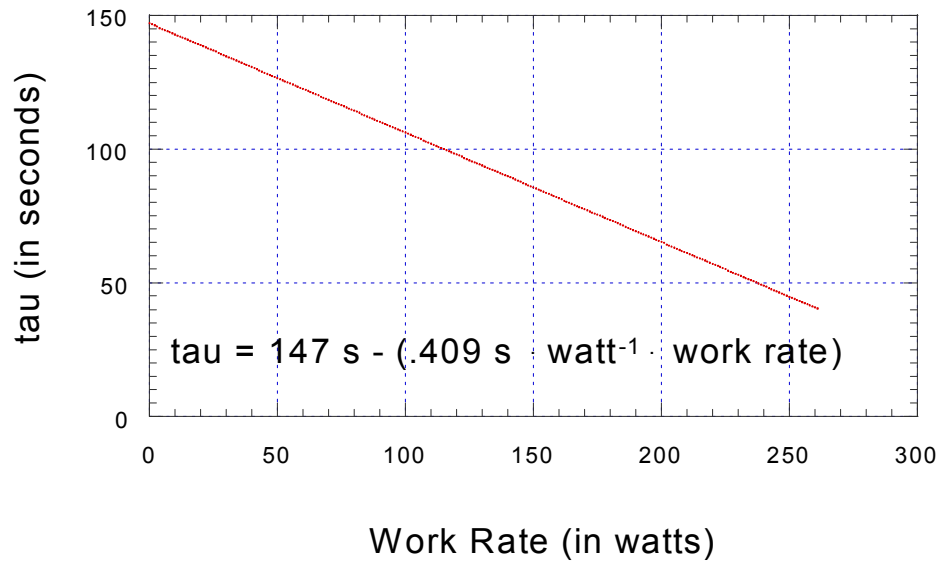
- Fast response Phase II is followed by a slow linear Phase III increase (i.e., the fast response begins at  $T = T_{D2}$ ) and the slow response begins at  $T = T_{D2}$  and ends at  $T = T_{D3}$  at which point there is no further increase in  $VO_2$

$$m1+m2*((m0 \leq 0)?0:((m0 \leq m5)?(1-\exp(-(m0/m4))):(1-\exp(-m5/m4))))+m6*((m0 \leq m5)?0:((m0 \leq m7)?((m0-m5)/(m7-m5)):1)); m1=400; m2=1900; m4=30; m5=180; m6=200; m7=360$$

## APPENDIX C

### RELATIONSHIP BETWEEN WORK RATE AND $\tau$

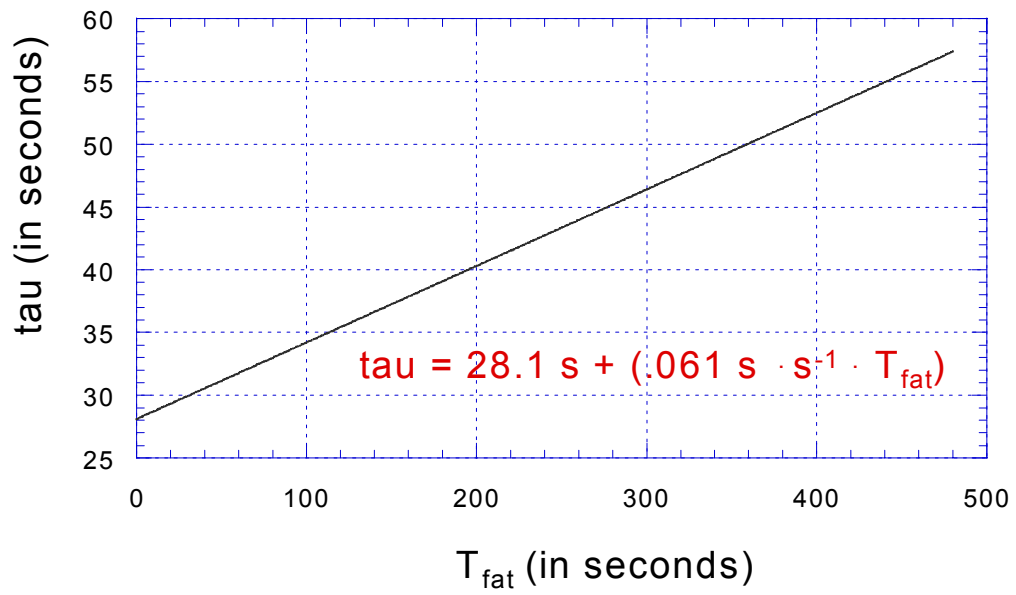
### Relationship between work rate and tau



APPENDIX D

RELATIONSHIP BETWEEN TIME TO FATIGUE AND  $\tau$

## Relationship between $T_{\text{fat}}$ and $\tau$



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